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A Survey on the Roles of Communication Technologies in IoT-Based Personalized Healthcare Applications

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ABSTRACT The vision of the Internet of Things (IoT) is to enable systems across the globe to share data using advanced communication technologies. With the recent technological advancements, IoT-based solutions are no longer a challenging vision. IoT will offer numerous and potentially revolutionary benefits to today's digital world. Future personalized and connected healthcare is one of the promising areas to see the benefits of IoT. This paper surveys emerging healthcare applications, including detailed technical aspects required for the realization of a complete end-to-end solution for each application. The survey explores the key application-specific requirements from the perspective of communication technologies. Furthermore, a detailed exploration from the existing to the emerging technologies and standards that would enable such applications is presented, highlighting the critical consideration of short-range and long-range communications. Finally, the survey highlights important open research challenges and issues specifically related to IoT-based future healthcare systems.

INDEX TERMS Internet of Things, network communication technologies, personalized healthcare, wearable sensors, standards, challenges.

I. INTRODUCTION

A survey conducted by the World Health Organization (WHO) in 2013 highlighted that "global health workforce shortage to reach 12.9 million in coming decades" [1]. Some of the main factors towards the decline were highlighted, including on the one hand decrease in interest of young people entering the profession, aging of already existing workforce and on the other hand growing risk of non-communicable diseases in people such as cancer, heart disease, stroke, etc.

Recently, "Personalized and Connected health" has provided a ray of hope to revolutionize the healthcare industry. Nowadays, health and fitness can be easily monitored and tracked with the help of wearable technologies like smart watches or smart clothes. Furthermore, elderly people can be managed remotely and thus hospital visits can be significantly minimized. Recent reports estimate that seven billion pounds per year can be saved by UK's National Health Service (NHS) by reducing the number of hospital visits and admissions using innovative technologies to provide quality healthcare to chronically ill patients remotely [2]. Personalized and Connected health has the potential to offer numerous benefits to patients, doctors or medical staff. For example, insulin pumps and blood-pressure cuff not only enable people to record and track their own vital signs but also make it possible for doctors and medical staff to monitor them remotely. This is also beneficial for patients as they receive instant treatment. Furthermore, connected health is especially beneficial for elderly people as they will be able to manage their health at home without the need for long-term hospital stays which is sometime depressing. Connected health also enable people to give access to their health data through different apps to their relatives, doctors or caregivers, resulting in numerous benefits.

Today's smartphones (which can act as on-body coordinators or central unit for personalized health monitoring) are equipped with a range of sensors including optical (to measure heart rate, blood glucose and pressure, oxygen saturation and other vital signs), ambient (for temperature, pressure, humidity measurements and so on), accelerometers,

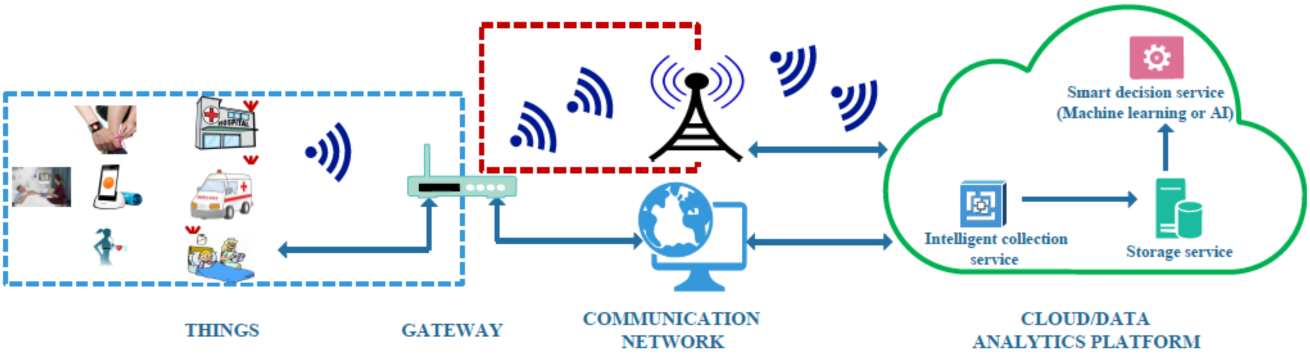


FIGURE 1. An overview of a typical IoT-based healthcare system.

magnetometers and gyroscope (to measure speed, direction and gravitational effects). Furthermore, built-in applications in smartphones (such as S-Health) can be used to keep track of daily fitness. However, there are concerns on the reliability, data privacy and security, cost effectiveness in the widespread use of wearable assistive technology and open source generic platforms.

In a classical personal health monitoring setup, wearable devices (including sensors, actuators, coordinators and gateways) constitute a wearable wireless sensor networks (W-WSN), where a coordinator is a key centralized controller which schedules the on-body deployed nodes communication patterns and collects the information from these nodes. Typically, such information can be further transmitted through a wireless or wired medium to the remotely located physician via gateways or base stations (and often termed as off-body communication). However, with the advent of body-to-body communication, the overall architecture and supported technologies for the connected health and safety applications is evolving [3].

In the future, personalized healthcare could not only enable remote monitoring and tracking but also diagnostics, early detection and pre-emption of diseases could be possible [4]. For such healthcare scenarios and applications, solutions based on an IoT architecture are promising. A typical IoT architecture can be subdivided into four subsystems which are as follows: things, gateways, communication network, and cloud services based infrastructure, as shown in Figure 1. A brief description on what is required to ensure reliable and efficient communication among these subsystems is as follows:

- **Gateways.** Also nowadays referred to as Fog nodes, they act as an intermediate node between sensors/devices and the cloud, providing the needed connectivity, security and manageability. However, in some IoT applications, rapid analysis is required based on the generated data. Let's take an example of a patient whose blood pressure is under constant monitoring. If the blood pressure is approaching the threshold limit, corrective measures must be taken immediately. However, the delay for blood pressure readings to travel from the user to the cloud for processing and analysis might result in loss of an opportunity to avert a patient fall. Therefore, analyzing data close to the device that collected the data (a.k.a. near-sensor processing) can make a huge difference in patient health diagnosis and prevent any danger. In this regard, new computing technologies like edge or fog computing are introduced to perform partial or complete data analytics either at the thing/device or at the gateway. With the advent of these technologies, the burden on the communication technologies will also be reduced and thus more and more things/device can be easily managed.
- **Communication Technologies.** One of the key issues in IoT-based applications is information sharing that requires appropriate communication technologies. **Better information sharing is a key – improving both the efficiency and the effectiveness of the service provided**. Particularly for real-time information sharing, reliable and secure connectivity is essential. No doubt, fixed line solutions are there but mostly too limited and expensive to implement. A flexible, cost-effective alternative which provides an answer is wireless communication networks. In term of wireless, a combination of both short-range communication such as Bluetooth, Zigbee, Wi-Fi and long-range communication technologies such as 3G/4G cellular or satellite systems are typically considered.
- **Cloud Infrastructure.** A cloud infrastructure is constituted of set of servers and storages that are linked together. To support IoT applications, such infrastructures run applications based on machine learning or artificial intelligence that analyze data from the device or thing in order to generate useful information that can be used for service or decision making.

  Machine learning, big data and artificial intelligence technologies have continued to revolutionize all industries by processing and analyzing massive amount of data in an efficient manner, giving meanings to raw data. With these advance algorithms, machines can analyze large set of information data and able to predict events and almost in real-time. With such capabilities, healthcare systems can not only help patients with early diagnosis or constant monitoring but also able to reduce cost of medical treatment and optimize their processes throughout the organization [5].

Creating a proactive framework based on predictive analytics is not only possible – it is the future of healthcare industry.

However, beside the availability of a wide range of technologies and systems that can constitute an IoT-based healthcare system, there is still a question that needs to be addressed, namely **"Which of the emerging IoT-enabled network communication technologies could fit to the specific requirements of the future healthcare?"**

To address this question, it is really important to understand the application-specific requirements of different emerging healthcare applications. Therefore, in this survey paper we presents a holistic view on the technological requirements of healthcare applications and provide extensive insight on the legacy and emerging communication standards and solutions. The main contributions of this paper are as follows:

- First, an extensive survey on emerging and futuristic healthcare scenarios is presented. In particular, three case studies on infectious diseases, musculoskeletal disorders (MSDs), and neuromuscular disorders are presented to highlight the future outlook and enhancements in these application scenarios. The specific requirements (i.e., latency, data rates, energy efficiency etc.) are presented. Next, in the below contributions it is evaluated if these requirements can be fulfilled by emerging communication technologies.
- Second, emerging standard and technologies are explored in detail ranging from legacy solutions and existing standards to emerging technologies. Both shot-range and long-range communication technologies are presented in detail and compared. Particular emphasis is given to the latest IoT standards (including both non-cellular and cellular supported standards). Pros and cons of these technologies are detailed, especially third generation partnership program (3GPP) recent options, including enhanced machine type communication (eMTC), narrow-band (NB)-IoT, and extended coverage global system for mobile communications (EC-GSM)-IoT. This article surveys the literature over the period 2000-2017 on wireless communication technologies (from legacy to emerging).
- Finally, open research challenges and opportunities related to the mapping of future applications scenarios to the emerging technologies are presented.

It is important to highlight the key differences and contributions of this survey with regards to other relevant existing surveys. Among the latest surveys, Islam *et al.* [6] covers the IoT-based healthcare technologies. Their focus is to survey the state-of-the-art network architectures, IoT-based services and applications with special consideration of various security issues in IoT-based healthcare systems. They also mention various regulations and policies for applying various IoT technologies to the healthcare domain. Another survey by Alam and Hamida [2] presents wearable human assistive technology and applications. It provides details of rescue and critical emergency and safety scenarios. It covers most of the legacy technologies and standards, particularly the IEEE 802.15.4 and IEEE 802.15.6 standards. The survey work conducted by Choudhary and Jain [7] also covers the legacy short-range communication technologies. Moreover, the surveys by Lin *et al.* [8] and Al-Fuquha *et al.* [9] present the legacy short-range communication protocol, as well as the integration of fog/edge computing and IoT, and its applications. The survey by Wang and Fapojuwo [10] presents, in a holistic manner, the PHY and MAC layer protocols for LPWAN solutions. Moreover, a number of efforts have also been devoted to security and privacy issues in IoT. For instance, the survey work conducted by Andrea *et al.* [11] presents the security and privacy issues in IoT technologies associated with physical systems, networking, software, and encryption. Similarly, the survey works in [12]–[14] also present the IoT applications, security challenges and counter measures. The survey by Ni *et al.* [15] presents the security issue in fog computing for IoT. Furthermore, the survey by Ida *et al.* [16] presents the security issue and challenges of IoT in the context of eHealth and clouds. In addition to the aforementioned survey papers, Botta *et al.* [17] considers the integration of cloud computing and IoT. Moreover, the survey by Verma *et al.* [18] presents the views to handle IoT data and different intelligence enablers for IoT.

Most of the existing surveys focus mainly on either too general (to provide a holistic view) or too specific aspects of IoT as mentioned above. To the best of our knowledge, personalized healthcare for various diseases, their technical requirements (e.g., latencies, accuracy, real-time, throughput, energy efficiency etc.) and mapping them onto existing (well established technologies) and emerging technologies to understand whether they can serve future applications or not is rarely addressed. This calls for a well-focused and comprehensive survey of IoT technologies for healthcare.

The focus of our survey is on future healthcare applications and their technical requirements and how such applications will be supported by the emerging technologies in terms of communication. **The main target is to investigate and highlight the requirements of future healthcare applications and discuss whether the emerging communication technologies are able to fulfill those requirement or not.** Furthermore, this survey also presents the open challenges and research issues that still need to be addressed to fulfill those requirements. However, it can be noted that one of the aspects which is not included in the scope of this survey is privacy issues in IoT as we believe it is mainly a governance and legislative issue. Questions such as the capture, processing and ownership of citizen's data will require new legislative frameworks to implement at the same time the framework should also avoid posing unnecessary constraints to IoT market.

TABLE 1. Examples of WBAN sensors and corresponding data rates (compiled from [19]–[21]).

Applications	Signals	Data Range	Frequency (Hz)	Resolution (bits)	Data Rate
Medical/Health	Glucose Concentration	0-20 mM	0–50	12-16	480–1600 bps
	Blood Flow	1-300 ml/s	40	12	480 bps
	ECG	0.5-4 mV	0–1000	12–16	6–48 Kbps
	Respiratory Rate	2-50 breaths/min	0.1-20	12	240 bps
	Pulse Rate	0-150 BPM	4	12	48 bps
	Blood Pressure	10-400 mm Hg	0–100	12	1.2 Kbps
	Blood pH	6.8-7.8 pH units	4	12	48 bps
	Body Temperature	32-40 C	0–1	12	2.4–120 bps
	Blood CRP	0-8 mg/l	-	12	2.4 bps
	Pathogen detection	0-1	-	12	2.4-160 bps
Non-Medical	High Quality Audio	-	-	-	1.4 Mbps
	Voice	-	-	-	50–100 Kbps
	Video	-	-	-	0.3–10 Mbps
	GPS positions	-	1	32	96 bps
	Motion Sensor	-	0–500	12–16	4.8–35 Kbps

In the overall context, the targeted audience of this paper includes the research community, clinicians, small and medium enterprises (i.e., telemedicine solution providers), entrepreneurs, policy makers and so on. This survey provides the reader with a full understanding of an end-to-end solution based on IoT architecture for future healthcare systems. Furthermore, by mapping the emerging technologies with the application-specific requirements of future healthcare system, this survey enhances the understanding within the research community and opens new research directions.

The rest of the paper is organized as follows. In Section 2, emerging and future healthcare applications and scenarios with their key characteristics are explored. This is followed, in Section 3, by a detailed state-of-the-art of emerging technologies with their pros and cons. Furthermore, open research challenges are addressed in Section 4. Finally, a conclusion highlights the main findings of this survey.

II. EMERGING APPLICATIONS

A. OVERVIEW OF HEALTHCARE APPLICATIONS

The use of digital technology is rapidly growing when it comes to healthcare, be it for monitoring, prediction, treatment, as well as getting and keeping fit. The improved overall performance (throughput, latency, reliability, ...) capabilities promised by 5G wireless networks paves the way for a new generation of healthcare applications ranging from remote health monitoring to video consultancy. Among other things, advances in terms of sensors, computing platforms, and radios are supporting the deployment of enabling technologies for acquiring, processing, analyzing and transmitting health-related data such as vital signs measurements, training information and activity of daily living (ADL) patterns, etc. Building upon the key concepts of WBAN and IoT, such technologies will enable the "health internet of things" or "internet of medical things" [22]. In what follows, we summarize healthcare related scenarios and highlight limitations that call for new telecommunication technologies that are expected to be covered under the 5G umbrella (see Section III).

- **Today:** Healthcare applications are usually built upon the typical three-tier model proposed in [24], namely intra-BAN, inter-ban, and beyond-BAN. The most common telemedicine applications today include monitoring of the heart-rate, blood pressure (BP), blood oxygen saturation (SpO2) and glucose level, body weight. In more sophisticated cases, electrocardiogram (ECG) data with Holter-like devices is applicable for cardiovascular disease patients as well. Due to the recent explosion of smart watches, physical activity tracking is getting popular as well. Table 1 exemplifies sensors that are typically found in WBAN applications and the corresponding data rates; this defines baseline requirements for the wireless connectivity. As can be noted, audio and video based monitoring and sensing is progressively emerging; however, as discussed later on, only the next-gen wireless connectivity will allow a more widespread usage thereof.
  Given the above requirements, many existing projects and commercially available devices rely on e.g. Bluetooth (IEEE 802.15.1) and/or ZigBee (IEEE 802.15.4), or more recently 6LoWPAN (that builds upon IEEE 802.15.4 and where each node has its own IPv6 address and can connect directly to the Internet) to wirelessly transmit the data collected by the sensors to a gateway. A more suitable approach would be to use IEEE 802.15.6 or SmartBAN (which are specifically designed for WBAN with low power, short-range, and reliability in mind), but compliant devices are yet to appear on the market.
- **Tomorrow:** Sensor technology is rapidly evolving thanks to advances in and the convergence of materials, physics, chemistry, biology, and electronics. These advances allow new types of sensors to be produced, but also to be miniaturized. Important technological advancements of sensors rely on flexible electronics and micromechanical devices. Today's sensors suffer from several drawbacks such as discomfort (e.g. still relatively bulky sensors and batteries), their possible

TABLE 2. Current and estimated peak network traffic at a university hospital in Germany. extracted from [23].

	2015	2025	2035
No. of beds	1100	1050	1000
No. of intensive care beds	35	70	100
Beds with full remote vital parameter reading	-	70	100
Traffic stream vital parameter readings	-	56 Mbps	80 Mpbs
IoT connections /bed	-	10	20
Traffic stream IoT	-	9 Mbps	88 Mbps
Imagery access count (Patient/day)	4	8	10
Traffic imagery access	49 Mbps	98 Mbps	122 Mbps
Live video streams surgery/room	-	1	2
Traffic live video streams surgery	-	150 Mbps	300 Mbps
Total peak traffic (without entertainment)	<100 Mbps	ca. 500 Mbps	ca. 600 Mbps

medical side effects (e.g. inflammation) and sometimes problematic accuracy (due to e.g. poor physical contact). To alleviate these drawbacks, approaches such as "tattoo-like" flexible and stretchable devices built using nanomaterial are being developed [25], [26]. It is also worth noting that these developments in flexible electronics also consider energy harvesting and energy storage [27]. Another example is micro and nano chemical sensors that can be used to detect chemical signatures with application to health monitoring [28].

Similarly, Lab-on-a-Chip (LoC) devices for point of care testing (POCT) build upon the latest advances in biosensors and liquid handling via microfluidics [4], [29], [30]. Although typically not worn on the body, POCT devices are expected to play an increasingly important role in on-site diagnostics, as a complement to remote monitoring. LoC In Vitro Diagnostics (IVD) tests are purpose-built for the detection of a single biological target and a single use [31]. After use, the part of the device in contact with the bodily fluid sample is discarded. The ideal LoC device is a palm-size, self-contained unit, which imposes restrictions on the dimensions of internal components as well as on the available power supply. Furthermore, the necessity to be disposable limits the variety of available structural materials. Novel LoC devices are capable of automated reporting of results through a wireless communication interface [32], which adds pressure on communication channels in terms of data-rate and bandwidth. Pathogen detection tests are designed for a single use and thus do not generate a significant load to data communication channels [30]. Quantitative enzymatic rapid tests (e.g. liver function tests) may be used for patient tracking on a daily basis in acute phases [33], or a monthly basis in chronic phases of medical conditions. The majority of these rapid tests only generates a few bytes of data, and as mentioned before, most are designed for infrequent or single use. However, their market presence will grow steadily in the next 3-5 years as will the availability of tests for various targets [29]. With a large user base reporting test results simultaneously, these tests may put a heavier load on data communication channels. This must be taken into account in future developments. An envisioned portable, networked LoC sensing platform is depicted in Figure 2.

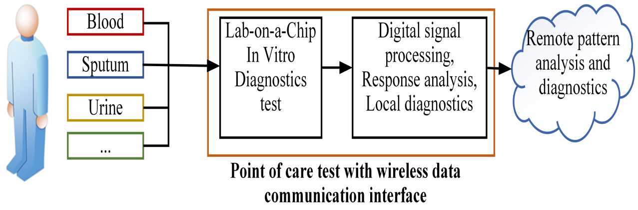


FIGURE 2. Envisioned portable networked point-of-care sensing platform, including a lab-on-a-chip in vitro diagnostic test, data processing and wireless data communication capabilities.

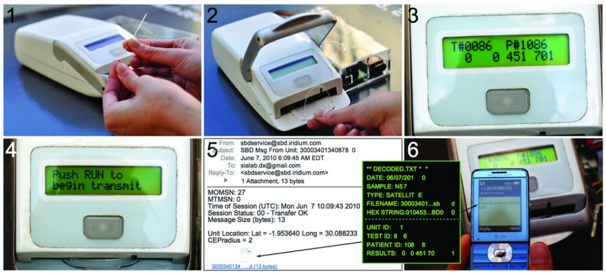
To the best of our knowledge, no systematic study of the wireless data-rates and bandwidth requirements related to the above emerging sensors has been published, most likely due to the fact that the core technologies are still being developed and few integrations into WBANs have been conducted so far. Nevertheless, coarse grain estimates have been proposed when it comes to a hospital environment. The study recently published in [23] presents current and estimated number of beds and corresponding peak network traffic at a university hospital in Munich (Germany). As can be seen in Table 2, whereas the total number of beds is expected to decrease from 1100 in 2015 to 1000 in 2035, that of intensive care beds is expected to increase from 35 to 100 and that of beds with full remote vital parameter reading is expected to increase from 0 to 100. At the same time, the study highlights the expected increase in terms of peak network traffic, for example from 0 to 88 Mbps for traffic stream IoT. Combined with live video streams for surgery, the study estimates that the total peak traffic (without entertainment) would reach 600 Mbps in 2035.

B. APPLICATION SCENARIO 1 – INFECTIOUS DISEASES

The prevalence and severity of infectious diseases in the modern world varies significantly by pathogen group [34]. While most previously lethal pathogens no longer cause high mortality rates, some still do, especially in less developed areas of the world. On the other hand, sexually transmitted diseases (STDs) for instance have a relatively high prevalence even in the developed world [35], and while typically not lethal, may still cause severe complications, such as infertility. Screening, followed up by immediate treatment and/or quarantining, can help contain an outbreak before it becomes an epidemic. POCT, and especially novel LoC devices can greatly contribute to preventive medicine by offering clinical-grade diagnostics to a wide audience at an affordable price. Especially with automated (mandatory) wireless results reporting, these devices could be game-changing in the field of infectious diseases, where typically treatments are more readily available than diagnostic tools. Rapid diagnostic tests (RDTs) by definition must meet the ASSURED (affordable, sensitive, specific, user-friendly, rapid, equipment-free and delivered) guidelines, which were established as part of an ongoing standardization effort in the field of these novel medical diagnostics [36]. First-generation POCTs are cheap (20-50 EUR per test), equipment-free RDTs that are readily available in pharmacies throughout Europe. They are typically serological tests implemented on lateral flow dipsticks. They take up to an hour to perform and require no user training other than to read a manual. These tests rely on an already present immune response and thus mandate an incubation time of a few days to a few weeks before they can detect the presence of an infection [37]. Furthermore, they do not offer the exact same performance measures as traditional clinical-grade tests.

All of these tests could be easily equipped with an automated readout system by adding a light source and a CCD camera (along with a processing unit and power supply), as it was demonstrated in the Clearblue Digital Pregnancy Test [38]. Adding a wireless communication interface to the reader is a simple task with the wide variety of Bluetooth 4.0 LE enabled microcontrollers available (e.g. those built around the Intel Curie module). On the other hand, most smartphones nowadays have digital cameras that offer great image resolutions (8-20 MP) as well as a light source; thus reading lateral flow strips with a companion app is also a viable option, and offers a chance to automatically report results to a central medical database. At present, a wide array of first-generation RDTs target STDs, such as HIV-1 or Chlamydia Trachomatis. Besides the detection of a direct immune response to the pathogen, monitoring serum biomarker levels, such as CRP (C-reactive protein, a non-specific inflammation marker), can also help determine the causes and monitor disease progression as well as treatment efficiency.

Second-generation POCTs rely on novel molecular diagnostics methods [37], that in terms of infectious diseases typically means nucleic acid amplification tests (NAAT). NAAT assays are the current gold standard in pathogen detection with PCR (polymerase chain reaction) being the most widespread and well-known protocol, used by virtually all clinics. However, for LoC, isothermal NAATs are far more suitable as they require only a single well-defined incubation temperature range for the reaction rather than thermal cycling as is mandated by PCR. NAAT, as the name suggests, amplifies the concentration of a target DNA to an easily detectable amount, against a noisy medium, such as a blood sample. The amplicons (amplified DNA) can then be visualized by adding marker molecules or detected by electrochemical sensors. Amplicons may be visualized on lateral flow sticks as with first-generation RDTs, offering the same option for readout integration as mentioned above. Electrochemical sensors are even better options for a higher level of integration, as the sensor and the processing unit can be manufactured within the same process and ideally packaged together on the same die [39].



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From:     sbdservice@sbd.iridium.com
Subject:  SBD Msg From Unit: 30003401340878 0
Date:     June 7, 2010 6:09:45 AM EDT
To:       sialab.dx@gmail.com
Reply-To: <sbdservice@sbd.iridium.com>
          1 Attachment, 13 bytes

MOMSN: 27
MTMSN: 0
Time of Session (UTC): Mon Jun 7 10:09:43 2010
Session Status: 00 - Transfer OK
Message Size (bytes): 13

Unit Location: Lat = -1.953640 Long = 30.088233
CEPradius = 2

3000340134 ...d (13 bytes)
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DATE: 06/07/201    0
SAMPLE: N57
TYPE: SATELLIT  E
FILENAME: 30003401...sb      d
HEX STRING:010453...BD0    0
--------------------------
UNIT ID:    1
TEST ID: 8   6
PATIENT ID: 108    6
RESULTS:  0  0 451 70        1
```

FIGURE 3. **The mChip is one of the first commercial examples of a handheld, self-contained, point of care test capable of detecting infectious diseases with a disposable lab-on-a-chip cartridge and automatically reporting results through a cellular broadband connection [40].**

LoC tests have great potential in decentralized medical diagnostics, but their commercialization is still at an early stage [29]. At present, only a handful LoC tests have been demonstrated with automated wireless reporting. The mChip by [32] Sia Lab is a portable, handheld, battery powered device that uses disposable LoC cartridges that perform ELISA (Enzyme-Linked Immunosorbent Assay) tests to detect antibodies specific for a certain infectious disease and transfers results to a central database through an integrated cellular broadband connection. The device was field-tested for HIV-1 detection [40]. The mChip platform can detect HIV-1 at 1/10 the cost of a benchtop ELISA assay, and it requires minimal user training. In essence, the mChip platform is a first-generation POCT with automated wireless result reporting as it relies on serological testing rather than a more reliable NAAT assay. At present, there are no second-generation POCTs with automated reporting, but commercial NAAT device examples exist, as well as there is a significant effort in the literature to implement them. The Alere Influenza A & B [41] is a prominent example of a portable NAAT test, which has automated result readout but no wireless reporting at this point. It is a reliable bench-top instrument for the rapid diagnosis of the Influenza virus at a lower cost and more rapidly than by traditional means. Gurrala *et al.* [39] demonstrated a LoC cartridge that would be powered and controlled by a PC through a USB port. The demonstrated cartridge was self-contained HIV-1 detection platform that relied on a NAAT assay and an integrated pH sensor to measure the concentration of amplicons.

C. APPLICATION SCENARIO 2 – CARDIOVASCULAR DISEASE

Cardiovascular diseases (CVD) such as coronary heart, high blood pressure, cardiac arrhythmia, and other cardiovascular problems are the leading cause of death worldwide [42]. A key factor related to cardiovascular disease is the presence of acute chest pain. However, it can also be caused by other medical problems and there are cases of cardiac arrests that are silent. In case of chronic hypertension periodic, i.e. daily blood pressure and body weight, measurements are sufficient for patient condition monitoring. However, the only reliable diagnostic tool available for assessing the probability of a cardiac event is electrocardiogram (ECG) monitoring. It represents the electrical activity of the heart as recorded from electrodes attached to the chest or/and extremities of a patient and is the most frequently performed test to evaluate the level of health of patients with malfunctioning or irregular functioning of the heart [5]. Compared to other vital signs measurements like heart rate, breathing rate, blood pressure, ECG requires significantly more data throughput. Traditional approach of ECG monitoring is based on Holter devices, which do perform recording of ECG signals, typically for 24 hours in the home environment. Then the signals are analyzed off-line to find any irregularities. Apparently, for some patients the cardiac events are rare, thus, continuous or at least long period monitoring with remote data access is beneficial. Also, real-time transfer of ECG signals to the hospital in case of an emergency situation has high potential of reducing response time in control or resuscitation of sudden-cardiac deaths victims [43]. On-line ECG monitoring is also useful for home-based rehabilitation after the cardiac surgeries. In this way the hospitalization time can be reduced but the active recovery of the patient cis possible under the professional surveillances.

With the advancement in wireless and mobile networks, ECG and simpler heart measurement results of CVD patients can be transmitted to the healthcare providers in real-time. WBAN is the essential part of the such systems as it allows the integration of data of sensor nodes attached to body or used during scheduled measurements. The objective of the current research is to address the challenge of providing quality care to cardiac patients anytime, anywhere along with reducing healthcare costs by leveraging the benefits of mobile technologies to enable remote monitoring of patients. Ubiquitous monitoring of heart for signs of cardiac events, which would have otherwise gone unnoticed, would not only promote early detection and treatment of cardiac disease, hence reducing the fatality rate due to cardiac arrests, but would also reduce un-necessary hospitalization by promoting remote monitoring of patients and thereby reducing healthcare costs [5].

In this regard, several architectural frameworks suitable for monitoring CVD patient wirelessly have been proposed. In [44], a smart vest is introduced with a variety of sensors integrated into the garment's fabric which simultaneously collects bio-signals in a non-invasive and unobtrusive way. The parameters measured by the vest include ECG, photoplethysmography (PPG), heart rate, blood pressure, body temperature, and galvanic skin response (GSR). Similarly, a novel hand-held device capable of collecting and wirelessly transmitting cardiac-related parameters such as ECG, PPG and bio-impedance is presented in [45]. Furthermore, several studies have successfully investigated contactless and leadless ECG monitoring [46]–[48]. A comprehensive survey of over 120 ECG monitoring systems were reviewed and classified into smart wearable, wireless, mobile ECG monitoring systems with related signal processing algorithms in [49]. Most of the monitoring system presented in [49] also include other vital sign monitoring measurements. The results of the review suggest that with the adoption of smart monitoring systems that measure vital parameters including ECG in real time, one can improve quality of healthcare system whilst reducing costs.

From a wireless communication viewpoint, the challenges that need to be addressed for such systems are the specific requirements in terms of power levels, data rates and latency. Due to the involvement of human life and health issues, a sufficient level of accuracy and high reliability is essential. In this regard, the data rate requirements set for CVD patient monitoring system can be classified as follows:

1) **Low data rate:** Periodic (once or twice a day) tests which consists of heart rate (HR), blood pressure and body weight measurements. Data resolution of 8 bit is sufficient for each measurement. A single measurement test with timestamp produces ca 10 bytes of data, the average data stream over time is negligible, and so is the required real-time performance. An important novel use case is real-time fall down detection that also does not produce significant amount of data.
2) **Medium data rate:** Applications that include single electrode pair (2 or 3 leads) ECG measurement producing a data stream of 12–16 bits @250 Hz-1 kHz sampling rate. As described above, real-time transfer of ECG signals opens new application possibilities for CVD patient remote monitoring and rehabilitation. Based on expert opinions, the efficient collaborative training under the assistance of distant clinician or physIoTherapist requires the end to end latency of ECG signals below one second. A commercial device which can be used for real-time observation of single channel ECG is Zephyr Bioharness 3. It has a resolution of 12 bit and 250 Hz sampling rate [50]. It is interesting that the device has a built-in accelerometer that allows to observe the patient activity level (100 Hz) and body posture (1 Hz). Actual (uncompressed) data rate of such single wearable ECG sensor is ca 3 Kbps, the motion data rate is ca 1.5 Kbps.
3) **High data rate** For the professional clinical assessment up to 12-lead ECG devices are used. Portable and wearable multi-electrode ECG measurements

devices usually have 5 channels and 16 bit @1 kHz resolution [51]. Sometimes EMG measurements capabilities (similar resolution to ECG, perhaps 2-3 channels) are additionally provided. For high-end monitoring of CVD patients, especially for home-based training support, it is wise to provide raw data of human motion or posture for the combined analysis. High-resolution motion capture, typically done with 9 degree of freedom (DoF) 16 bit inertial motion sensors (IMUs) @50–250 Hz sampling, allows to reduce the impact of motion artefacts to electrical signals, understand the measurement context and therefore improve the assessment quality. Data fusion and pattern recognition can be done on fog nodes, which is more preferred nowadays, or in the cloud. Use of machine learning techniques is applicable in both cases. For the remote monitoring and real-time human assistance, the network delays should not exceed one second as by the previous requirement class. Normally, multichannel ECG and EMG remote monitoring usually requires data throughput of 120 and 60 Kbps respectively [52]. Such data bandwidth also allows simultaneous transmission of raw data of 1–3 motion sensors.

Beside the challenge of providing such real-time and reliable communication service, processing an accurate diagnostic in real-time is also of crucial importance. For such systems, advance machine learning processing techniques need to be included. However, there is also a provision to address these problem with the help of edge or fog computing concepts close to the device that reduce delays and also minimize the burden on communication technologies. The overview of such provision for future healthcare system will be discussed in later sections.

D. APPLICATION SCENARIO 3 – MUSCULOSKELETAL DISORDERS

Musculoskeletal disorders (MSDs) are injuries and discomforts that affect the human body's movement or musculoskeletal system. The parts of the body that can be affected by MSDs include hands, wrists, elbows, neck, shoulders, and vertebral column. MSDs are one of the most prevalent occupational disease in the European Union (EU); among the workers in all sectors they are often referred to as "Work-related musculoskeletal disorders (WMSD)" [53]. According to the European Occupational Diseases Statistics (EODS) data collection, the most common occupational diseases are musculoskeletal diseases [53]. Based on the latest survey from the Labor Force in Great Britain, 41% of the work illness is due to MSDs [54]; similarly, it is the dominant health related problems among the working population in the EU [55]. Such facts and statistics are spread worldwide as reported by the Canadian Center for Occupational Health and Safety in [56] and Safe Work Australia in [57] and so on.

The factors contributing to MSDs include, but are not limited to, work postures and movements, repetitiveness and pace of work, force of movements, vibration, temperature, increased pressure (e.g., to increase productivity), and the lack of or poor communication [56]. In certain workplace conditions as shown in Fig. 4, for example, the layout of the workstation, the speed of work (especially in conveyor-driven jobs), and the weight of the objects being handled all influence these factors.

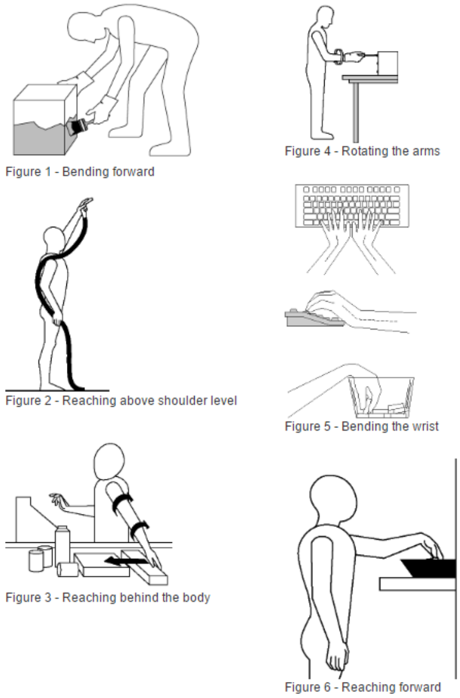
Figure 1 - Bending forward
Figure 4 - Rotating the arms
Figure 2 - Reaching above shoulder level
Figure 5 - Bending the wrist
Figure 3 - Reaching behind the body
Figure 6 - Reaching forward

FIGURE 4. **Various captured postures and movements among occupational workers that can lead towards possible musculoskeletal disorders [56].**

There are a number of studies carried out on various occupational workers including computer and office workers [58], nurses, caregivers and paramedical staffs [55], [59], with focus being on identifying the prevalence of MSDs. They cover the discomforts and disorders in neck/shoulder, fingers/wrist/hands, upper and lowers back pains etc. These studies rely on huge set of data collections across various professionals among different countries and continents. However, the existing data collection methods are dominantly based on surveys and questionnaires which are often not very accurate. Mostly, the estimated percentage of particular positions and postures are obtained based on mere guesses. This leads to serious concerns on the accuracy of such data collections.

In order to improve such data collection methods, miniaturized wearable and implant sensors and devices can be used. The portable sensing platform presented in Fig. 2, can be exploited in the context of MSDs. It can help to obtain accurate and precise positions, postures and orientations, load measurements on different bones and so on. To that end, it is envisioned to exploit the data collections at various levels. First, at the local level, POCT and diagnostics results

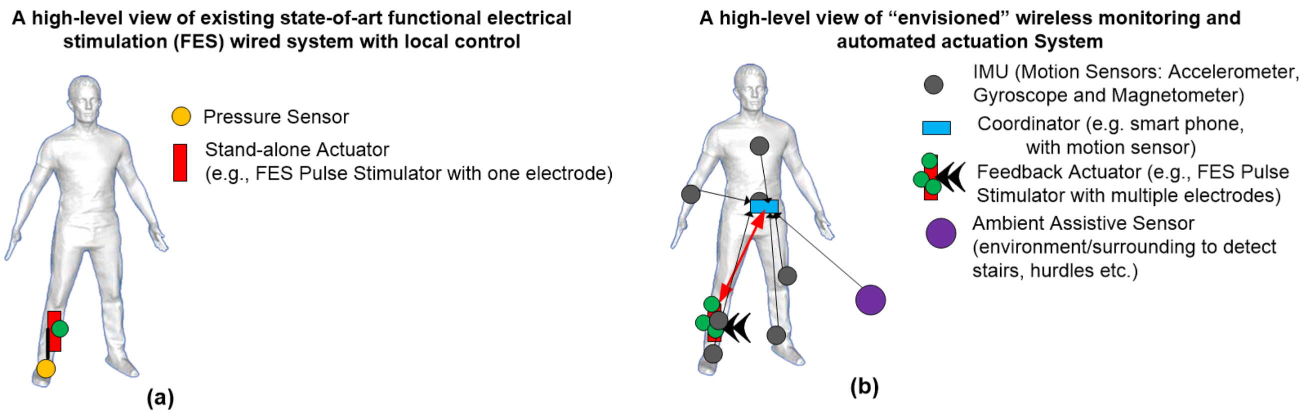

FIGURE 5. Neurodegenerative disease monitoring and actuation for assistive living.

can warn the workers with alarms or warnings for possible hazards due to their consistent wrong postures and movements. The local level processing and decision process can also be considered to have deployed infrared cameras to monitor and keep track of the movements and by performing Gait analysis early warnings and cautions can be provided to the workers [60].

Another important aspect is the remote level monitoring, processing diagnostics and early detections of the possible MSDs, in which accurate and precise informations from the deployed sensors and devices could be transmitted to the remote cloud for long-terms predictions and estimations. Such systems could primarily exploit machine learning algorithms and techniques for big data analytics; these are covered as one of the challenging aspects later in Section IV.

E. APPLICATION SCENARIO 4 – NEUROMUSCULAR DISORDERS

Today's telemedicine and eHealth systems, including wearable and mHealth solutions, are oriented to user data collection and off-line information sharing services between the user and clinician. This implies rather soft QoS requirements to the real-time performance and reliability of the communication channels. Advanced remote sensing applications like the above mentioned LoC systems also do not set hard requirements to communication channel quality. The situation is more complicated for closed loop systems that include certain actuators. For example, there is a need for assistive technological solutions for neuromuscular disease patients in terms of physical walking aid and fall prevention. In fact, there are about 40 million neurological disease patients and neurological disorders contributing to more than 90 million disability-adjusted life-years (DALY) worldwide in 2005 [61]. In this context, electrical muscle stimulation is a novel treatment method of tremors of Parkinson's disease [62]. Furthermore, metronomic pacing sound may help recovering from Parkinson's off-periods [63]. Certain stroke, ataxia, traumatic brain injury patients may benefit of electrical muscle stimulation for gait improvements [64].

There exist electrical stimulators which can activate the muscles of patients having neural impairments. For example, commercial assistive foot drop devices, i.e. [65], [66] can activate heel muscles during the walking with electrical signals and therefore significantly reduce the falling risk of patients. The electrical stimulator may be manually controlled over a wireless link [67] or, in modern systems, by a wirelessly connected pressure switch under the sole Fig. 5-a. According to human haptic feedback studies, the latencies should not exceed ca. 50 ms to achieve the feeling of instant feedback or reaction [68].

However, the existing stimulators, both manually or sole sensor activated, still operate as standalone solutions not taking into account changing environmental context and other health parameters of the patient. For example, the standalone operation does not take into account specific conditions such as the presence of ice or stairs on the way or risen heart rate of the patient. Unreliable (wireless) communication between sole sensor and stimulation actuator due to e.g. network congestion may be harmful to patient's safety. Therefore, connectivity solutions for wearable actuators have to provide certain deterministic QoS levels, also while several external context information sources are present. An idea of a modern context sensitive electrical muscle stimulation system is proposed in Fig. 5-b.

For the (heel) muscle activation, additional information besides of sole sensor is used. IMUs attached to the human body provide body posture information that is essential for timely fall prevention. External sensors provide information about the environment i.e. walkway surface conditions, in-or-outdoor context and specific patient related information like relapse condition presence, low blood pressure or heart rate.

To elaborate the application (clinical) requirements, let's consider an IMU with accelerometer, gyroscope and magnetometer having 9 DoF. Each individual sensor has nowadays 16 bits of precision, i.e. 48 bits for (X,Y,Z), with a resolution of 100 Hz, yielding an application payload of 14.4 Kbits (nearly 2 KB/IMU). Having 3 to 4 IMUs with an actuator, the coordinator has to manage an application payload of nearly 10 KB within 50 ms. For the above, corresponding

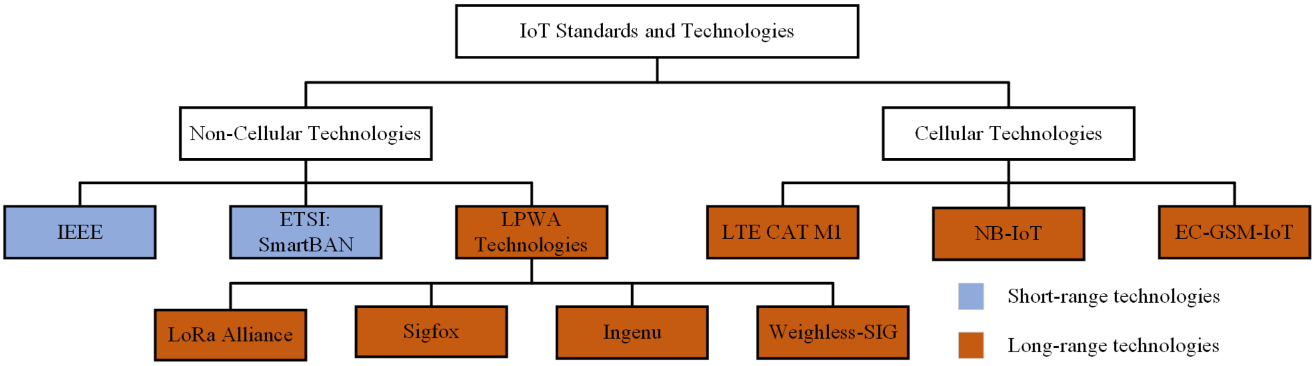

FIGURE 6. Enabling standards and technologies for IoT.

technology selection is not trivial. The Continua Health Alliance of medical device manufacturers has certified Bluetooth and Zigbee technologies for wireless communication. However, with the growing number of ubiquitous and pervasive medical devices, specific wearable and BAN technologies and standards such as WBAN (IEEE 802.15.6), MBAN (IEEE 802.15.4j) and recently SmartBAN, were specifically introduced for medical applications.

Summary: To conclude on the four above case studies, for the future healthcare applications, the combined emergence of new types of sensors and their numbers, actuation capabilities, the amount of data and possible data-rates (especially for video), ultra-low power utilizations, higher quality of service and reliability will push the existing wireless communication standards and technologies to their limits. Moreover, new, stricter requirements on communication service quality of WBAN solutions are likely to be set. This calls for a move from legacy technologies to the next-generation standards and technologies, as discussed in details in the next section.

III. ENABLING STANDARDS AND TECHNOLOGIES

Over the last decade, a number of standards have been used for body-oriented applications highlighted in the previous section. In this section we provide an extensive analysis of various standards proposed by governing bodies such as IEEE, ETSI, 3GPP etc. The objective is to highlight the strengths and weaknesses of these proposed standards and to understand the suitability of these technologies in future healthcare systems. To do so, we have classified these standards as cellular and non-cellular which are then further divided into short-range and long-range communication protocols, as shown in Fig.6.

A. LEGACY STANDARDS OPERATING IN UNLICENSED SPECTRUM

These standards use the unlicensed spectrum and are typically non-cellular infrastructure-based which are often easy to deploy depending upon customized applications.

1) IEEE STANDARDS

Over the last two decades, IEEE standard association (SA) has proposed a wide range of standards to satisfy various applications requirements. In particular IEEE 802.11 a/b/g/n/ac etc. (for Wi-Fi), IEEE 802.11p (vehicular communications), IEEE 802.15.4 (WSN), IEEE 802.15.1 (BL) and IEEE 802.15.1 (BLE) are widely used in short-range communication. With reference to body sensor networks, initially IEEE 802.15.4 and its variants were used as a readily solution for WSN and lately IEEE 802.15.1 is also becoming popular in wearable and medical devices.

Most of the above mentioned communication standards were not designed specifically for wearable wireless sensor networks (W-WSN). Therefore, they do not meet the specific requirements set forth by W-WSN applications [2]–[19]. For example, there are major limitations in terms of peak-power consumption, achieved data rates, communication range, generated RF interference's, and efficient on-body and body-to-body communications. To this end, the IEEE 802.15.6 and IEEE 802.15.4j standards are specifically designed to meet the W-WSN applications requirements. IEEE 802.15.6 standard proposed a greater flexibility and provisions to tune the standard based on given applications design requirements. At the physical layer, the standard includes three options (i.e., human body communication, narrow-band and ultra-wide band communications) with different operating frequencies and data rates. Whereas, at the medium access control layer, distributed (CSMA/CA), scheduled access (TDMA), unscheduled access as well as poling and posting options are available. More details and comparison of W-WSN specific standards can be found in [2]and [19].

2) ETSI: SmartBAN

ETSI established a Technical Committee (TC) named SmartBAN in 2013 for the development of new standard considering the specific constraints and requirements for W-WSN. A new set of specifications, covering the PHY [69], and MAC [70] layer, have been approved by this TC in December 2014, but the detailed technical specifications

TABLE 3. Technical specification for SmartBAN.

Parameters	SmartBAN Requirements
Coexistence/robustness	Good (low interference to other systems, high tolerance to interference)
Data rates (Sensor)	Nominally $<$ 100 Kbps/node (vital sign monitoring)
Transmission rate (PHY)	Up to 1 Mbps
Network topology	Star network
QoS control	Priority based control Cross layer optimization. Emergency signal transmission supported.
Reliability	Robust to shadowing Robust to multipath interference
Max. node capacity	up to 16 nodes (typically 8)
Range	$<$ 1,5 m
Latency	$<$ 125 ms

are pending publication by ETSI. The initial technical requirements retained by TC SmartBAN for WBAN parameters are listed in Table 3 [71].

The expected SmartBAN-based solutions will mainly support on-body communication, body-to body communication, and links to implanted devices. Furthermore, SmartBAN is based on a multi-radio approach in which devices can be connected using exiting radio standards. SmartBAN operates in the ISM band of 2.401-2.481 GHz and uses Gaussian Frequency Shift Keying (GFSK) modulation. There is also a provision to employ BCH coding (127,113) and repetition coding to reduce errors if required.

The key feature of the SmartBAN protocol is the division into the Data channel for data transmissions and Control channel for network initialization and transmitting control messages. The benefits of having separate control channel include fast channel acquisitions and easy BAN-to-BAN communications. On the contrary, if the control channel faces interference, significant changes such as node association and channel change are not possible in the Data channel [72].

Moreover, the data transmission is divided into Inter-Beacon Interval (IBI) which constitute of three main components which are as follows: Scheduled Access Period (SAP), Control and Management period (CMP), and Inactive Period. SAP is mainly for data transmission with time division multiple access (TDMA) to avoid collision. CMP is used for both control and data transmission and is operated by slotted Aloha. Other than these access protocols, an alternative Multiuser Channel Access (MCA) mode has also been defined which enables transmission of high priority messages such as emergency packets. This is particularly important for guaranteeing very-low latency for time-critical applications [72]. However, these features are unique to SmartBAN protocol and are not supported by other standards for W-WSN, e.g., in IEEE 802.15.6.

This section focused on typical on-body communication. In the next section, we highlight the next communication tier, i.e. body-to-body and off-body communication and upcoming emerging technologies.

B. LOW POWER WIDE AREA TECHNOLOGIES

Non-cellular Low Power Wide Area (LPWA) technologies are promising technologies to meet the diverse requirements set forth by future IoT application. These technologies can operate in coexistence with the traditional cellular and short-range wireless technologies to enable connectivity for low power and low data rate devices, which is currently not supported by these traditional technologies. Forecasts for LPWA opportunities and connections are tremendous; it is expected that numbers will increase from 59 million (in 2016) to 83 million (in 2017) and will reach 3 billion connections in 2025 [73].

The major target applications for LPWA technologies include, but are not limited, to smart city, personal IoT applications, smart grid, smart metering, logistics, industrial monitoring, agriculture, etc. One of the potential applications for LPWA technology is in smart health and remote wellness monitoring system. These systems constitute of W-WSNs that communicate over long-range wireless links to send or receive information. Specifically, LPWA technologies are considered for delay tolerant applications that require low data rate, low power consumption and low cost. One such example is the remote monitoring of the patients at their homes which typically does not have stringent time requirements.

Furthermore, most of the LPWA technologies are based on star network topology in which each sensor/node communicates directly with the base station. This results in highly asymmetric link between a node and the base station. As in most of the IoT applications, the data traffic is mostly from node to base station and traffic from base station to node consists of only acknowledgment or simple commands or actions to be performed. This asymmetric nature helps to put all the complexity on the base station, resulting in simple end devices with low cost and better battery life. On the other hand, this also impacts negatively on the scalability and quality of service provided by LPWA technologies.

At this moment, there exist several competing non-cellular LPWA technologies such as Sigfox, LoRA, Ingenu, Weightless-SIG and Telensa, each employing various techniques to achieve long-range, low power operation, and high scalability. The detailed comparison of all these competing technologies is presented in Table 4.

1) SIGFOX

The Sigfox technology uses Ultra Narrow Band (UNB) technique and operates in the sub-GHz ISM band [74]. UNB operation is achieved using channel bandwidths lower than 1 kHz. This enables Sigfox to have low noise levels and operate with ultra-low power resulting in a maximum throughput of 100 bps. However, on the other hand, this also results in high receiver sensitivity and inexpensive antenna design. Due to ultra -low power consumption, Sigfox uses Binary Phase Shift Keying (BPSK) modulation for data transmission.

The low data rate offered by Sigfox limits the number of use cases for this technology.

Furthermore, Sigfox is based on a star network topology and the initial version of the technology only support uplink communication. However, the latest version can support bidirectional communication with significant link asymmetry. This technology is fit for applications that require to send only small data traffic such as alarm systems, HR monitoring, or sending alert to rescue services which mostly requires only one-way communication.

2) LoRa ALLIANCE

LoRa Alliance LPWAN solution is based on two major components, namely LoRa and LoRaWAN [75] and operates in sub-GHz ISM band.

LoRa is a physical layer technology that uses a chirp spread spectrum (CSS) scheme for modulation. The main idea of CSS is to spread a narrow band signal into a wider channel bandwidth making it harder to detect as it has noise-like properties. Furthermore, LoRa also introduce six different orthogonal spreading factor (SF) for achieving variable data rates depending on the application-specifications. This results in improved spectral efficiency and increase in network capacity. To improve the robustness of the communication, LoRa includes a variable cyclic error correcting scheme as well [76].

The LoRaWAN is a network layer protocol using simple ALOHA scheme in combination with LoRa to enable multiple device to communicate in a star topology. The LoRaWAN is optimized specifically for low power consumption devices. To support diverse IoT applications, LoRaWAN classify three classes of LoRa end devices with different latency and power requirements. Class A support devices which require ultra-low power consumption but are highly delay tolerant. These devices listen to downlink for a short interval of time immediately after the uplink transmission, otherwise, remains in sleep mode. Class B support devices that require low power consumption and moderate latency requirements. Class B devices schedule reception from the base station at fixed time periods. Therefore, these devices only wakes-up at those intervals on which the transmission is scheduled. Therefore, utilize more power than Class A devices. Lastly, Class C support devices that require the smallest possible latency and, therefore, have to listen continuously the downlink transmission. Furthermore, LoRaWAN also provide secure communication using symmetric-key cryptography while authenticating the end devices with the network. [76]

From a data rate perspective, LoRa provides better data rates than Sigfox and is ideal for data transfer rates between 300 bps and 5000 bps. However, one of the major drawbacks in using LoRa LPWAN solution is that it requires a subscription from a single vendor (Semtech), which might be costly.

3) INGENU

Ingenu was formerly known as On-Ramp Wireless. Ingenu is operating in the 2.4 GHz ISM band that provides high transmission power, thus enabling higher throughput and more capacity than other technologies operating in the sub-GHZ band. On the contrary, operating on 2.4 GHz gives it a shorter range than Sigfox and LoRa, and makes it more vulnerable to interference. Furthermore, Ingenu uses a patented access scheme named as Random Phase Multiple Access (RPMA) employing direct sequence spread spectrum (DSSS) multiple access [77]. RPMA technology employs tight transmit power control and have high receiver sensitivity [78]. High level of receiver sensitivity provides good signal power while maintaining significant capacity level. This allows large coverage area with low cost access point simultaneous with extreme capacity while optimized for long battery life and enterprises grade security. An RPMA access point can also support hundreds of thousands of end devices with various data rates.

4) RPMA TECHNOLOGY

supports the IEEE 802.15.4k specifications. The data rate offered by Ingenu is typically in the hundreds of thousands of bits per second which is higher than Sigfox and LoRa, but at the cost of shorter battery life. Furthermore, Ingenu has its own precise tracking protocols and does not require a separate global navigation satellite system (GNSS) module for tracking applications like Sigfox and LoRa. Similar to LoRa, Ingenu is capable of bidirectional transmission which is currently not supported by Sigfox. However, in terms of number of users supported per base station, Sigfox and LoRa are better choice than Ingenu.

5) WEIGHTLESS

Weightless is an open LPWA standard. It operates in the sub-GHz unlicensed spectrum. Weightless comprises three open standards, each providing different features, range and power consumption [79].

- **Weightless-P.** This standard provides bi-direction communication and uses Gaussian Minimum Shift Keying (GMSK) and Quadrature Phase Shift Keying (QPSK) modulation schemes. The standard offers the committed performance rate, network reliability and security parameters as given by 3GPP solutions. This standard offers a data rate in the range between 0.2 Kbps to 100 Kbps and provides substantially lower cost than other LPWA technologies. A full support for acknowledgments and bidirectional communication capabilities enable over-the-air upgrades of firmware as well.
- **Weightless-N.** This standard offers one-way communication and uses a star network architecture. Weightless-N devices have a long battery life of ten years and have low network cost. Weightless-N uses differential binary-shift keying (DBPSK) modulation scheme and operates in sub-GHz band with ultra-narrow band technology. This standard uses frequency hopping

TABLE 4. Comparison of LPWA technologies.

Parameters	SIGFOX	LORA ALLIANCE	INGENU	WEIGHLESS-P	WEIGHTLESS-N	WEIGHTLESS-W
Modulation	UNB/ GFSK/DBPSK	CSS	RPMA-DSSS, CDMA	GMSK, offset-QPSK	GFSK	16-QAM, BPSK, QPSK, DBPSK
Band	sub-GHz ISM	sub-GHz ISM	ISM 2.4 GHz	sub-GHz ISM or licensed	sub-GHz ISM	TV White Space (470-790 MHz)
Data Rate	10-100 bps	0.3-50 Kbps	8 bps-8 Kbps	200 bps-100 Kpbs	30 Kbps-100 Kbps	1 Kbps-10 Mbps
Range	10 km (URBAN), 50 km (RURAL)	5 km (URBAN), 15 km (RURAL)	3 km (URBAN), 10 km (RURAL)	2 km (URBAN)	3 km (URBAN)	5 km (URBAN)
Topology	Star	Star on Star	Star, tree	Star	Star	Star
Link Symmetry	No	Yes	No	NA	Uplink only	NA
Devices per access point	1 Million	1 Million	$\leq$ 500,000	Unlimited	Unlimited	Unlimited
MAC	Unslotted Aloha	Unslotted Aloha	CDMA	TDMA/FDMA	Slotted Aloha	TDMA/FDMA
Power Consumption	Tx: $\leq$ 50 mA, Rx: $\leq$ 10-40 mA, Sleep: $\leq$ 0.01 mA	Tx: $\leq$ 50 mA, Rx: $\leq$ 10-40 mA, Sleep: $\leq$ 0.01 mA	Tx: $\leq$ 750 mA, Rx: $\leq$ 300 mA, Sleep: $\leq$ 0.072 mA	NA	NA	NA
Encryption	No Support	AES 128b	16B hash, AES 256b	AES 128/256b	AES 128b	AES 128b
Mobility Support	NO	Yes	Yes	Yes	Yes	Yes
Location Support	NO	Yes	Need GPS	NO	NA	NA
Over the air update	NO	Yes	Yes	Yes	NO	NA

algorithms to reduce interference. Weightless-N provides support for mobility as well.

- **Weightless-W.** This standard operates in the TV white spaces spectrum and able to support several modulation schemes including 16-Quadrature Amplitude Modulation (16-QAM) and Differential-BPSK (DBPSK) and a wide range of spreading factors. Because of the wide range of modulation schemes, the standard is able to provide peak data rate between 1 Kbps and 10 Mbps. Furthermore, for better battery life, the end device operates in narrow band with low power than the base station. However, one of the major drawbacks in this standard is that it can only be permitted in few regions so far.

Like LoRa, all Weightless standards employ symmetric key cryptography for securing application data.

C. CELLULAR/LICENSED STANDARDS

The legacy non-cellular wireless technologies mentioned in the previous section are not ideal to connect devices which are distributed over a large geographical area due to their coverage limitation. These technologies can be deployed for a specific area (i.e., home, hospital) and will not be able to provide global coverage, which is the requirement of many IoT applications such as smart city, logistics and personal healthcare [80]. To improve the range of these technologies, one must use dense deployment of devices and gateways in a multi-hop mesh network which incurs huge deployment cost. On the other hand, traditional cellular networks already having a global footprint might be a suitable option. But these cellular technologies are not able to achieve high energy efficiency to support ten years of battery lifetime for the end devices. Furthermore, the complexity and cost of cellular devices are also very high as they must deal with complex waveforms to manage voice and high-speed data services. There is a need to strip complexity and cost of such devices by reducing their functionalities for applications that require low-power communication.

However, in the context of IoT, there is a need to have multiple technologies to meet the requirements of Massive IoT applications which can coexist with each other. Thus, the mobile industry is standardizing several LPWA technologies, including Extended Coverage GSM (EC-GSM), LTE-M1 and NB-IoT. All these solutions meet massive IoT requirements, and can complement each other based on technology availability, use case requirements and deployment scenarios. Table 5 presents 3GPP IoT Standards specifications. The key common features among the three options includes effective power saving modes (PSM) and eDRX (Extended Discontinuous Reception) techniques which allows the cellular networks to exploit low data rate applications with a battery life of around 10 years.

Regarding the PSM, typically in LTE, the user equipment (UE) is said to be in idle mode when it is not connected to eNB, still the network keeps track of the UE by means of a paging mechanism. After the initial power-on sequence, the UE will perform limited functionality in idle mode and save a lot of battery power due to discontinuous reception. The UE is paged for DL traffic but for UL traffic the UE will no longer be in idle state; it will move to the connected state [81]. However, in new IoT standards,

TABLE 5. 3GPP IoT standards specifications.

	LTE-M1	NB-IoT	EC-GSM-IoT
Deployment	In-band LTE	In-band, Guard-band LTE, Standalone	In-band GSM
Coverage (dB)	155.7	164	164 (with 33 dBm power class), 154 (with 23 dBm power class)
Downlink	OFDMA - 15 kHz tone spacing, Turbo Code, 16 QAM, 1Rx	OFDMA, 15 kHz sub-carrier spacing, tail-biting convolutional code (TBCC), 1Rx	TDMA/FDMA. GMSK, 8PSK (optional), 1 Rx
Uplink	SC-FDMA, 15 kHz tone spacing, Turbo code, 16 QAM	Single tone, 15 kHz and 3.75 kHz spacing, SC-FDMA, 15 kHz tone spacing, Turbo codes	TDMA/FDMA. GMSK and 8PSK (optional)
Bandwidth	1.08 MHz	180 kHz	200 kHz
Data Rates UL/DL	1 Mbps - both for UL and DL	DL: 250 Kbps UL: 250 Kbps (Multi-tone), 20 Kbps (Single-tone)	
Duplexing	FD, HD, FDD and TDD	HD, FDD	HD, FDD
Power Saving	PSM, ext. DRX	PSM, ext. eDRX	PSM, ext. DRX

an LTE-M11 device (see below) that transmits once per day in full PSM mode could last well over 10 years on 2 AA batteries [82].

1) LTE CAT M1 STANDARD

LTE-M1 is part of 3GPP Release 13 and operates on lower bandwidths of 1.4 MHz. The main target of LTE-M1 is to provide low complexity, increased coverage and improved battery life, while allowing reuse of the LTE installed base. Due to the bandwidth limitation, a new control channel and a frequency hopping mechanism were specified. However, most of the legacy LTE-broadcasted signaling for synchronization and system information remains the same. Furthermore, LTE-M1 includes PSM and eDRX to extend battery life up to 10 years or more. The combination of low bandwidth and reduced transmission power will result in more cost-efficient and low-power design. LTE-M1 traffic is over a full LTE carrier, and it is therefore able to tap into the full capacity multiplexed of LTE. Additionally, new functionality for substantially reduced device cost and extended coverage for LTE-M1 are also specified within 3GPP. Even with the reduced complexity, LTE-M1 UEs are still able to provide similar features as legacy LTE UEs, including connected mode mobility and seamless hand-offs, efficient scheduling of frequency packets through semi persistent scheduling (SPS), and low latency packet while in connected mode [83]. All these features open the possibility for a LTE-M1 UE to integrate voice in IoT applications as well.

2) NARROW-BAND IoT STANDARD

NB-IoT is a long-term evolution (LTE) variant designed specifically for IoT. Like LTE, NB-IoT is based on orthogonal frequency-division multiple access (OFDMA) with 180 kHz system bandwidth, which corresponds to one physical resource block (PRB) in LTE transmission. With 180 kHz of minimum spectrum requirement, NB-IoT can be deployed in three possible operational modes which are as follows:

- Stand-alone as a dedicated carrier. In stand-alone deployment, NB-IoT can occupy one GSM channel of 200 kHz.
- In-band as part of the wideband LTE carrier, just like LTE-M1 but uses one physical resource block (PRB) of LTE with 180 kHz.
- Within the guard-band of an existing LTE carrier with one PRB.

To support such flexible deployment scenarios, NB-IoT reuses the LTE design extensively, such as OFDM in downlink and single carrier frequency-division multiple access (SC-FDMA) in uplink [84]. In addition, new features are also added to ensure the demands of IoT based applications. Key design changes from LTE include synchronization sequences, random access preamble, broadcast channel and control channel. NB-IoT is designed to allow long-range communications at a low data rate among devices, such as sensors operated on a battery in delay tolerant applications. The key feature of NB-IoT is that it can be easily deployed within the current cellular infrastructure with a software upgrade, result in reduced deployment cost. Furthermore, NB-IoT can provide data rate of 250 Kbps for the multi-tone downlink communication and 20 Kbps for the single-tone uplink communication. Furthermore, for coverage extension, the concept of repetitions and signal combining techniques are introduced.

Moreover, to achieve high energy efficiency, NB-IoT employs battery saving features such as PSM and eDRX. These features help NB-IoT devices to have battery life more than 10 years. The device complexity of NB-IoT is also reduced compared to LTE-M1 devices and other unlicensed LPWA technologies, and it will be ideal for addressing ultra-low-end applications in markets.

3) EC-GSM IoT STANDARD

Like LTE, 3GPP has also proposed the extended coverage GSM (EC-GSM) standard that aims to extend the GSM coverage using sub-GHz band for IoT applications. Similar to NB-IoT, EC-GSM also uses the repetition and signal combining for the coverage extension. However, to provide variable data rates to meet the diversity of IoT application, two modulation techniques, namely Gaussian Minimum Shift Keying (GMSK) and 8-ary Phase Shift Keying (8PSK) can be used for data transmission. The peak data rate that can be achieved with 8PSK is 240 Kbps. Like other cellular standards, EC-GSM can be deployed with a software upgrade in GSM network. Moreover, the standard has also improved the security features compared to conventional GSM and is able to support around 50 K devices per base station.

Summary: Undoubtedly, in IoT-based solutions, communication technologies play a vital role. Particularly, in case of connected healthcare systems, reliable and delay intolerant communication is required. In this regard, cellular communication technology already has a global footprint and thus supporting and driving IoT adoption is considered to be more viable. However, for an end-to-end solution, there will be a need for merging multiple standards and technologies into one system. The detailed overview on the resulting research challenges are provided in Section IV by mapping the above mentioned technologies on the requirement set by application presented in Section II.

IV. MAPPING OF FUTURE APPLICATIONS AND TECHNOLOGIES: RESEARCH CHALLENGES AND OPPORTUNITIES

The healthcare industry is changing at rapid pace, the advancements in technology is playing a vital role in improving the health services. In the future, it would be more important to have early detection and pre-emption of the diseases which can be harmful and can create ripple effects on the public health, health services and capabilities, as well as financial budgets. As highlighted in Section II, the possible healthcare scenarios, in particular widespread diseases such as MSDs, require attention. The key to such problems is the early identification of diseases; in the near future, the exploitation of the IoT-enabled technologies can help to overcome the existing limitations. Below we highlight some of the important open challenges and future research opportunities.

A. HETEROGENEOUS TECHNOLOGY FOR EMERGING HEALTHCARE APPLICATION

In the context of healthcare applications, there are many factors to consider while choosing an appropriate technology such as node cost, network cost, battery lifetime, data rate (throughput), latency, mobility, dynamic range, coverage, and deployment model. No single technology will be able to excel in all factors simultaneously. Furthermore, most of the healthcare applications will require on-body, in-body or off-body communication. Therefore, a combination of short-range and long-range communication technologies will be needed.

In this regard, for short-range communication, SmartBAN can be considered as a good match as it offers both on-body and in-body communication, which results in an increased number of applicable use case scenarios. Furthermore, it is also the only short-range technology that is fully optimized for healthcare applications. Furthermore, it is based on an heterogeneous multi-radio approach, as mentioned in Section III-A.2, with low interference to other systems and high tolerance to interference. Thus, it can coexist with the long-range communication standards as well. However, considering specific FES stimulation requirements (detailed in Section II-E), the achievable throughput within 50 ms is only 6.25 Kbytes. This highlights the weakly addressed time constraints of actuator based systems in BAN specific standards, as most of them consider 125 ms upper-bound end-to-end delay.

Furthermore, the standard is currently under development and further standardization for power consumption and interoperability is needed to help open the market. Also, technical advances are needed to make BAN devices and solutions that are unobtrusive, more convenient to the user and dependable.

On the other hand, for long-range communication, the key requirement of healthcare applications are low cost, frequent communication and QoS such as remote patient monitoring for heart disease [85] or ECG monitoring [86]. Most of the LPWA technologies are not able to offer the same QoS as a cellular protocol; however, they are optimized for low cost, high volume solution. On the other hand, cellular protocols can provide guaranteed QoS, but they do not offer comparable spectrum cost. Furthermore, LPWA technologies like Sigfox and LoRa, the end device can sleep for as little or as long as application desire due to asynchronous, ALOHA-based protocols. However, in cellular protocols, the end device has to periodically synchronize with the network at constant intervals resulting in increased energy consumption. The synchronization has been reduced in new cellular protocols such as NB-IoT but still an issue that need to be addressed.

Moreover, modulation in cellular technologies like OFDM or FDMA requires linear transmitters that require more peak current compared to non-linear transmitter modulations such as LoRa. This results in faster battery drain in cellular technologies. On the contrary, cellular technologies provide short latency and high data rate. Therefore, for applications that require frequent transmission with high data rate and low latency, cellular technologies will be the best option. However, for applications that need long battery life and infrequent transmission, LPWA technologies might be a better choice.

B. NETWORK AVAILABILITY AND LOCALIZATION

Other essential requirements for healthcare applications are network availability and localization. One useful advantage of the cellular technology is that the existing infrastructure can be upgraded to deliver the service; however, this can be viable for a dense city environment that has or will have 4G/LTE coverage as the deployment is restricted to a cellular base station. It is not ideal for rural or suburban areas that do not or will never have 4G coverage. In this case, LPWA technologies like Lora or Sigfox will be a better choice. Localization in a cellular system is typically very accurate and can be easily achieved with a careful network deployment and planning. On the other hand, due to the limited bandwidth and absence of direct path, it is really hard to get error free localization in LPWA technologies [76]. Thus, doing accurate localization using LPWA transceivers alone is a real challenge.

C. RESOURCE MANAGEMENT

In the future, the healthcare applications are expected to operate as an underlay or overlay communication with the existing communication technologies like 5G or Wi-Fi, thereby creating an heterogeneous network (HetNet). Furthermore, the deployment of various IoT devices will unplanned, along with an aggressive frequency reuse scheme, generate severe interference between adjacent cells, degrading system performance. Therefore, to provide a suitable solution for the IoT use case scenarios like healthcare, one has to optimize the required throughput, delay and device density with novel resource management algorithm, which will be a challenging task. It can be noted that cellular standards such as NB-IoT (that have the provision to operate within the LTE band) will experience inter-cell interference from the users of the neighboring cell. The other LPWA technologies that operate in unlicensed spectrum band will be affected by the neighboring WiFi users or other transmissions.

Furthermore, in healthcare applications, the data size is usually quite small (e.g. comprising of few bytes), particularly for applications like heart rate monitoring, sweating, blood pressure, etc. For such a small data size, cellular technologies like NB-IoT might not be a suitable option because of high control channel overhead cost. The use of such technologies for applications like healthcare, without robust resource allocation, will result in inefficient utilization of radio spectrum [87].

Moreover, most of the proposed standard for long-range communication deal with delay tolerant applications, whereas applications like healthcare are subject to strict delay constraints. To enable the lower delays and higher reliability, current long-range communication protocols such as NB-IoT need modifications; some of them are as follows:

- Reduced transmission time intervals by increasing the sub-carrier spacing between the OFDM symbols will enabling fast and efficient data transmission;
- Enabling early channel estimation by redesigning physical channels;
- Providing fast and reliable decoding of data transmission by using convolution codes and block codes for control channels;
- Implementation of high diversity levels improving the reliability of signal detection and decoding, as well as availability.

D. SECURITY AND PRIVACY MANAGEMENT

With the advent of IoT, the potential security risk that could harm the user will also increase. These risks are mostly associated with unauthorized access and misuse of personal information. Although these risks exist with tradition communication networks, they are heightened in the context of IoT. With the increase in number of IoT devices connected to the network, the vulnerability that an intruder can attack and fetch the information will also increase. Moreover, in healthcare application, these risks are more significant and can lead to serious situations which can lead to death. For example, an unauthorized person might exploit security and get access to the network to control the insulin pump attached to a patient. By getting such access, he can now change the setting of these devices so that they are no longer deliver medicine, or an attacker could also change the reports of the patient, leading to an inaccurate diagnosis by the doctor or medical professional. Such attacks would put the patient's lives at serious risks.

Dealing with such attacks in IoT is really challenging because of three main reasons. Firstly, incompetence of companies entering the IoT market in dealing with security issues. Secondly, the target of IoT is to have low cost devices which eventually result in devices that are not highly sophisticated to deal with such concerns. Thirdly, most IoT devices will be operating on unlicensed spectrum technology for short-range connectivity with limited QoS and security requirements typically applicable for a home or indoor environment. The combination of short-range and long-range communication technologies will even result in reduced security for long-range communication protocols, as hacker will be looking for new doors to enter the networks.

In addition to risks to security, privacy risks are also of paramount importance. Most of these risks are due to the direct collection of sensitive personal information, such as precise geolocation, financial account numbers, or health information which are already present in traditional Internet and mobile commerce. However, from the perspective of IoT, the main risk arises from the information such as persons behavior pattern, sleeping order, habits, locations, and physical conditions over time.

Given the above discussion, it can be concluded that the combination of multiple technologies will be required to serve the diverse need of IoT applications. The application requirements, deployment scenario and costs will dictate which technology is used for specific application. Both cellular and non-cellular LPWA technologies have different strengths and weaknesses. Therefore, in the future, they are likely to be complementary, rather than competitors.

E. DATA ANALYTICS

The healthcare industry is handling enormous amount of data which is produced by official records, regulation requirements for different aspects of patient [88]. Wearable devices for healthcare applications and data produced by these give us the chance to learn the pattern of user behavior to estimate the future impact. These data will grow exponentially in upcoming years due to the huge popularity of wearable devices. Big data grows rapidly in terms of velocity, veracity, value, variety and volume [89]. Analysis will be increasingly complex for these huge amount of personal data and also to update the knowledge base. Consequently, this complexity demands big data analytics solutions for the domain of wearable sensors. Big data analytics consists of suitable tools which are able to tackle the massive data through edge, fog or cloud computing, machine learning, artificial intelligence and pattern recognition techniques. Data collected from wearable sensors need some methods to make it comprehensible for detecting the causality of different diseases.

Existing methods for data analytics are typically based on self-reporting (i.e., questionnaires, interviews, and surveys) observation methods or expert assessments. These methods suffer from limitations and are not sufficient for the objective assessment of the exposure (e.g., different postures and movements for MSDs, discussed as a case study in Section II). However, by using measuring equipment on persons helps to provide quantitative and objective measurements of postures and movements, muscular load during the work for MSDs [90]. To find out the exposure-response relationship is one of the critical aspects of the research for the prevention of diseases. IoT is reshaping the future healthcare by collecting critical data from the patients, providing communication among different sensors, processing capabilities of fog/edge nodes and applying data analytics to fuse the useful information that is useful for patients or stakeholders. To send a real-time appropriate feedback to the patient after analyzing the data in an IoT based healthcare architecture is an open challenge for the future healthcare system. Moreover, to find out the proper online exposure-action relationship on actual time for the diseases is challenging task for the IoT based platform.

Complex event processing (CEP) is a promising approach that helps to enable the real-time data analysis. The main purpose of the CEP is detection of the complex event patterns from the semantically low-level events such as sensor, log, or RFID data and generate/trigger a signal/activity for that pattern matching. Determination of rule patterns from these simple events based on the temporal, semantic, or spatial correlations is the main task of CEP systems [91]. In the current design, experts provide event rule patterns for the CEP systems. However, the flourish of big data and IoT provides an opportunity to automate the determination of rule patterns in CEP domains. Machine learning algorithms help to automate the determination of rule patterns for CEP. To propose an online and efficient machine learning algorithm for the determination of rules/exposure-action relationship in CEP is a challenging aspect and recent trend of research.

Defining the complex events in a generalized way for healthcare applications is also a challenging aspect to reuse the different signal processing capabilities. To define a simple and expressive grammar for complex event processing (CEP) is ongoing research to achieve the job of semantic definitions, the required inputs, outputs, and logic. Moreover, to understand the nature of different health analytics, it is necessary to develop a generalized platform which is also a challenging aspect for future healthcare data analytics.

In addition to the data processing architecture, machine learning based methods require specific tuning to learn a classifier over a large scale datasets [92]. Dimensionality reduction and feature selection help to improve the dimensionality reduction. Whether supervised or unsupervised, machine learning algorithms always require the regular learning steps to obtain a mapping for knowing the rule sets. Some machine learning algorithm, e.g., deep learning involve several layer transformation of the data in order to obtain the high-level abstraction [93]. Now, for dealing with the big data, special considerations should be given to the complexity of these methods.

From the software point of view, processing big data is linked to the parallel programming paradigm, e.g., MapReduce. Moreover, there are some open source architectures, e.g., Hadoop is considered for storing distributed databases in a scalable framework where some tools like Cascading, Pig, Hive which allow to develop different applications to process big data on clusters [94]. However, when combined with the continuous streams of data this requires capabilities for iterative and low-latency computations depending on sophisticated models of in-memory computation and data processing.

Another challenge is where to place the fog/edge computing in the system for data analytics? Do future healthcare applications really need this technology or is cloud computing enough? As the sensor nodes for healthcare applications have challenges due to their tiny size, energy efficiency, limited computing capabilities and memories, future healthcare application scenarios are not matched with the local sensor node processing for the huge amount of real time data. By means of IoT, sensor nodes can forward the data to the cloud for processing using communication standard e.g., 6LoWPAN over IPv6 [95]. But this device-to-cloud infrastructure is not feasible for so many cases. For example, the regulations do not allow to store the data outside of the hospital and there are also chances of data center failures. So, there is a need for a distributed system where the data processing capabilities will reside not only in a centralized data center but also in some other devices between sensors and clouds, i.e., fog/edge computing.

Data privacy is another important issue which is regulated by laws in most countries. For preserving the privacy issue, data must be linked to the right person which ensures correct diagnosis and treatment. Therefore, the collected data from individual must be tagged with an unique identifier. Moreover, data security should be ensured at all levels of the healthcare system including at the sensor level.

The major challenge of data analytics for future healthcare system is to predict acute and longer-term physiological changes which will occur under the progression of disease. There is a huge amount of health records that can support this but the transformation into relevant information is the most difficult and challenging aspect.

V. CONCLUSION

The healthcare sector is adopting the IoT very rapidly. Exponential growth of the wearable devices, powerful communication technologies and cloud based data analytic methods are providing a new era of future healthcare systems. Mapping the different applications of the IoT in future healthcare associating with the recent network communication technologies is very important for exploring the future research challenges and directions. Furthermore, in order to deal with the huge amount of data by selecting the most suitable methods for data analytics is also an indispensable requirement for future healthcare applications. This survey paper presents advances in IoT-based future healthcare for various use case scenarios, explores the recent and emerging communication technologies and standards in IoT.

As a whole, it can be concluded that for most of the application scenarios such as infectious disease, musculoskeletal and neuromuscular disorders, current communication technologies are able to meet the requirement in terms of reliability, connectivity, data rate and latency. However, an amalgamation of technologies will be needed to have an end-to-end solution for emerging healthcare applications. This will raise new research questions such as how will these technologies coexist or how will these communication technologies impact the transmission characteristics in such heterogenous scenarios? Furthermore, for application like cardiovascular diseases, which requires near real-time processing of data and stringent delay and data rate constraints, current technologies lack to satisfy such requirements. There is a need for new reliable and ultra-low latency communication protocols along with advance computing architectures.

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